PAUL SCHERRER INSTITUT

Electrostatic Kicker at 37kHz and +/-10kV for Muons

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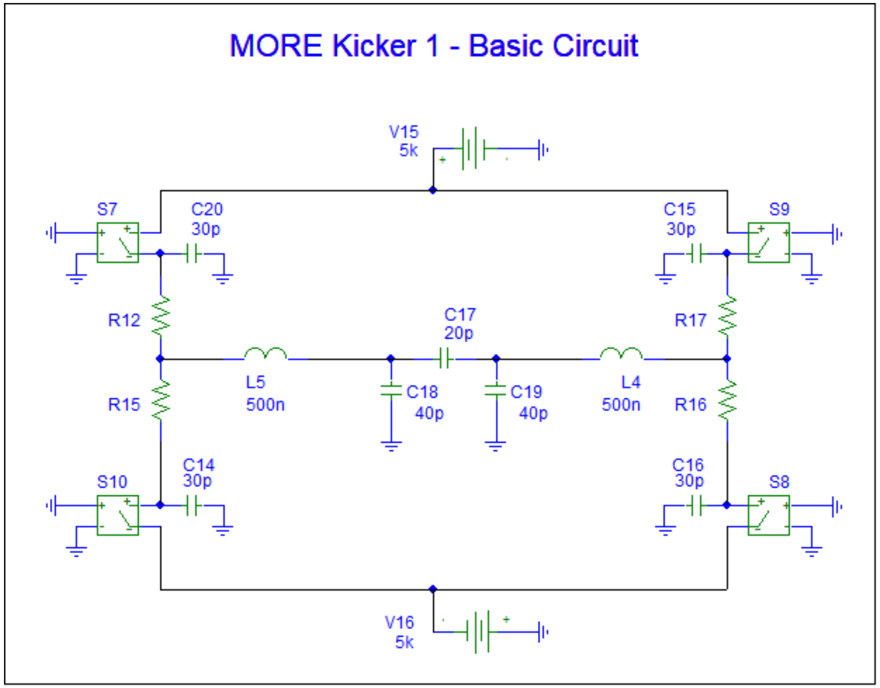
PULPOKS Workshop DESY, 22-23 April 2023

Requirement

Purpose	Switching of few 30 MeV muons after measurement of arrival of a single muon in an experimental station
Voltage between capacitor plates	+/-10kV
Latency	<50ns
Rise Time	<50ns
Rep rate	27us
Amplitude stability	<+/-5%
Radiation	Single muons only, no radiation constraint

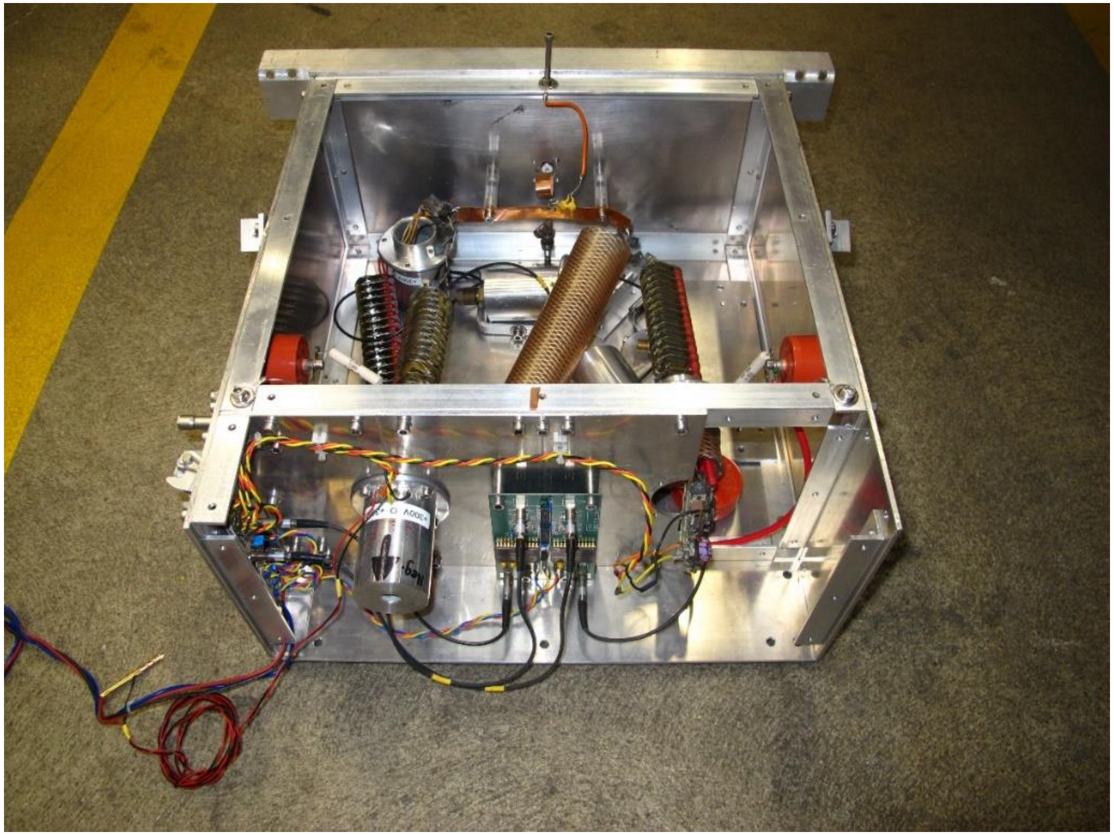
GPS MORE / LTF parasitic :

LTF MORE / GPS parasitic :



Present Design - 1

Present Design- 2



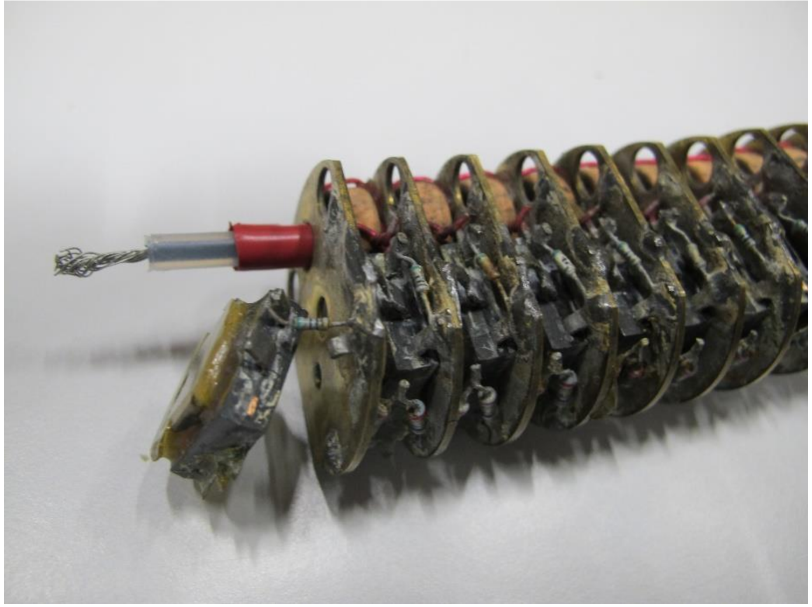
Original Enclosures -

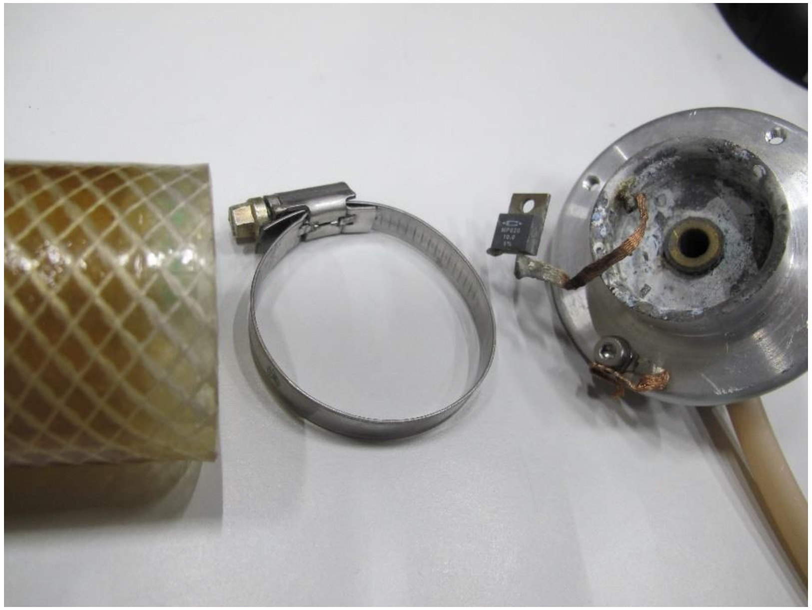
Inside are two switches for half H-bridge.

Two enclosures are mounted on the vacuum tank to drive the capacitor plates differentially.

PVC hose pipes enclose switches and carry FC77 coolant

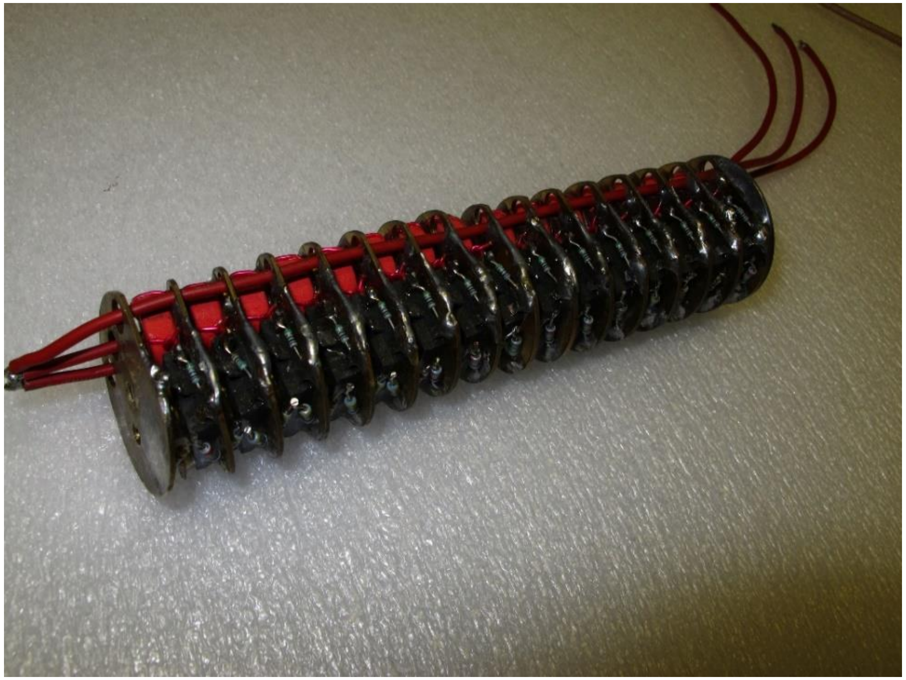
Present Design- 2





18 years operation
Water leak into coolant destroyed the switches
10 years waiting for a repair

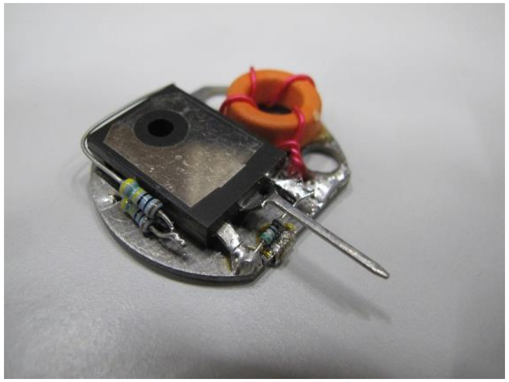
Present Design - 3

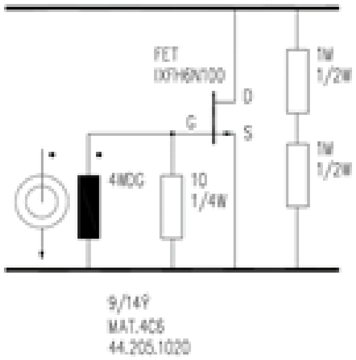


Fifteen IXFH6N100 in series

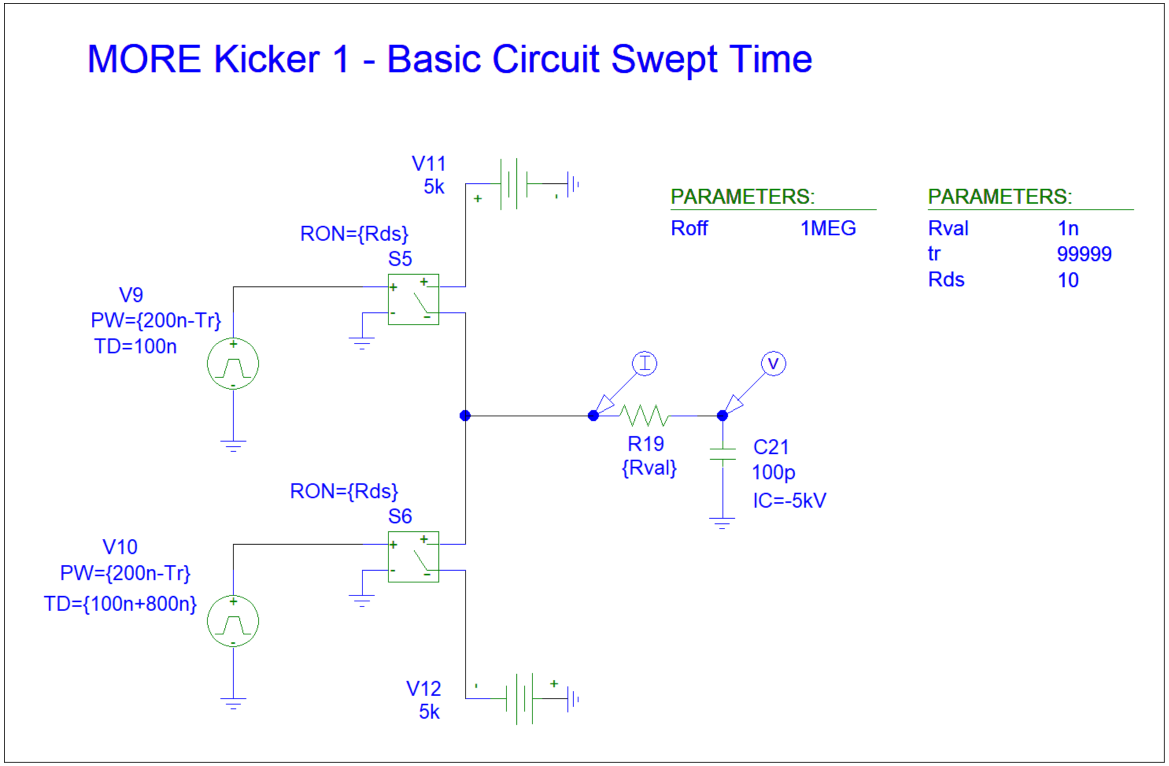
Single loop primary pulse turns all FETs on simultaneously

Series resistors in TO220 packages also present (not shown here)





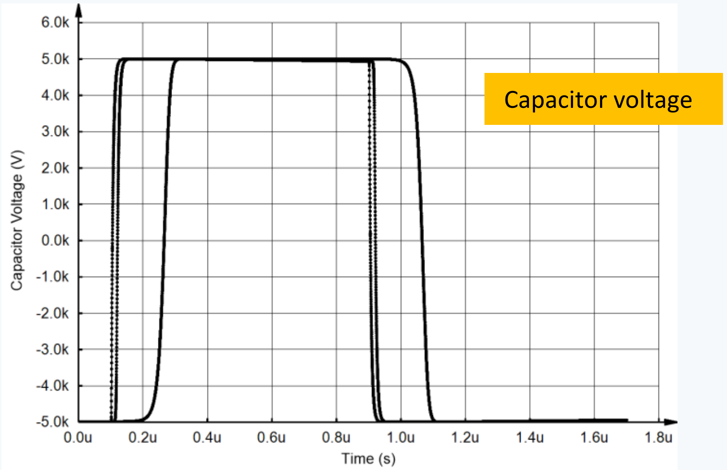
Fundamental Limit for Energy Loss / Dissipation - 1

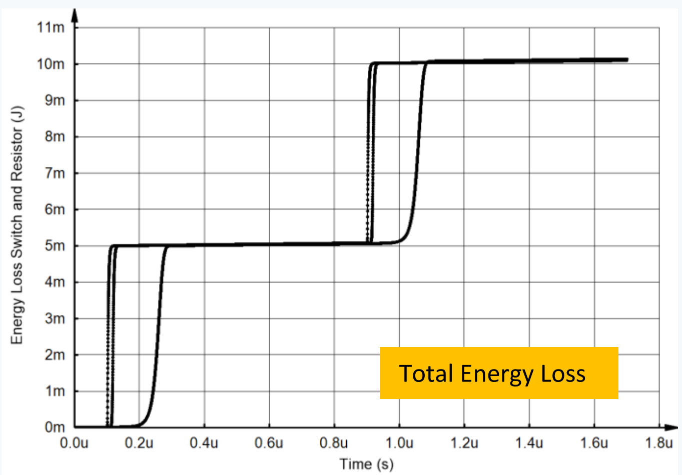


A fundamental aspect of charging and discharging capacitance is that the energy dissipated is constant, independent of switch transition time and series resistance

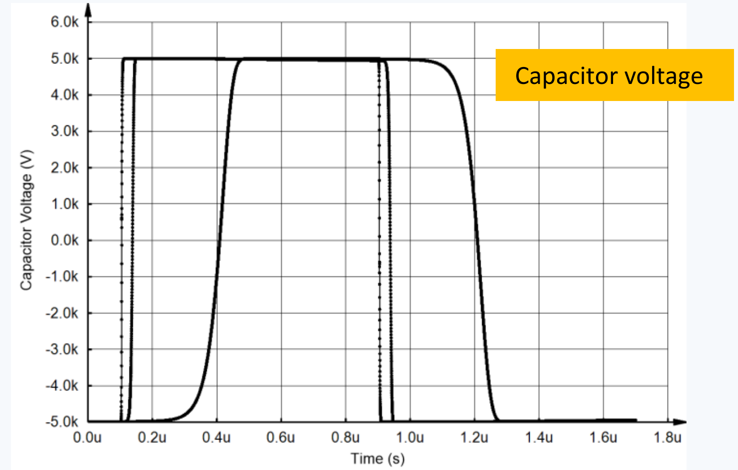
Fundamental Limit for Energy Loss / Dissipation - 2

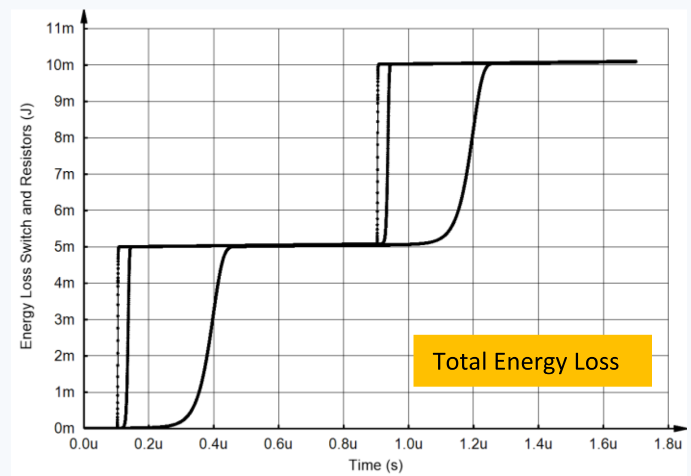
External Resistor 50Ohms (whatever)
Switch resistance zero
“Rise Time” tr=5ns, 50ns, 500ns





Switch resistance 10Ohms (whatever)
External Resistor zero
“Rise Time” tr = 5ns , 50ns, 500ns





Fundamental Limit for Energy Loss / Dissipation - 3

A fundamental aspect of charging and discharging capacitance is that the energy dissipated is constant, independent of switch transition time and series resistance

Consequence is:

- no reduction of total dissipation by increasing speed of switching
- to spread dissipation over more packages, preferred to use higher resistance FETs as well as additional series resistors

Expect ca. 1100W dissipation from the four switches, with ca. 12W per TO-247 package

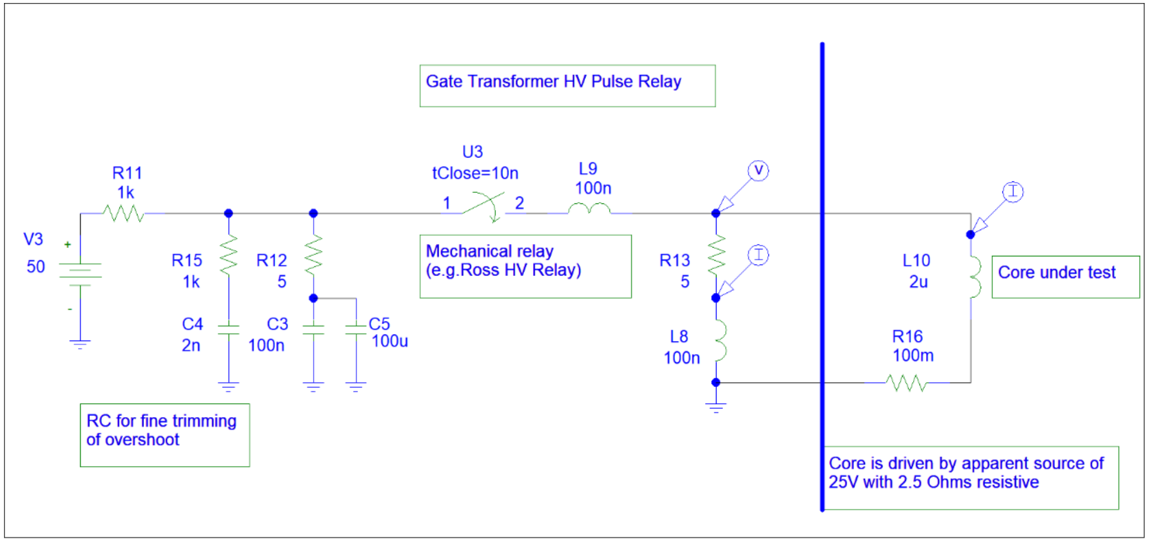
Fundamental Limit for Energy Loss / Dissipation - 4

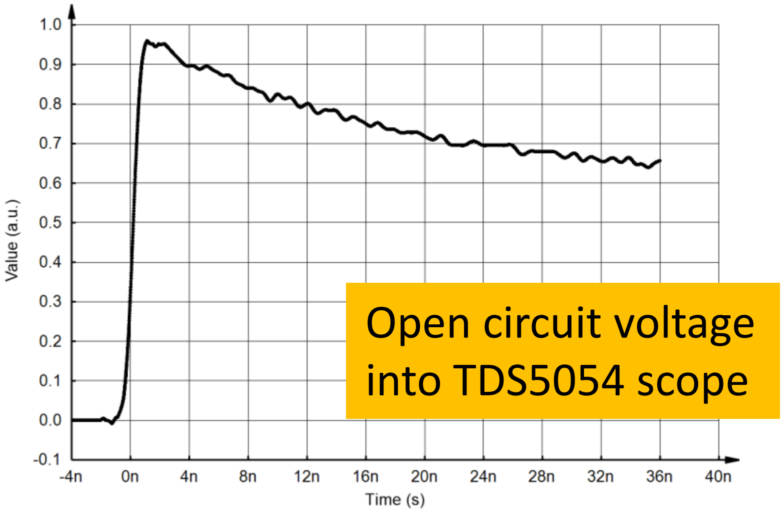
Selection of FET is not critical, but if switching speed is increased, the FET dissipation is decreased. The additional series resistance must then take the extra impulse energy.

	Year	V	Idc	Rds	Qg	Ciss	Tdr	Tr	Tdf	Tf	Spice	Avail.
IXYS Littel												
IXYS Power												
IXFH 6N100	2000	1000	6	2.0	88	2600	35	40	100	60	y	
IXFH 6N100 Q	1999	1000	6	1.9	48	2200	10	15	22	12		
IXFH 6N120 P	2005	1200	6	2.6	92	2830	24	11	60	14		
IXFH 12N90	2015	900	12	1.0	56	3080	32	34	50	68		
IXFH18N100 Q3	2020	1000	18	0.66	90	4890	37	32	40	13	y	
IXYS RF												
IXZR 08N120	2009	1200	8		39	1960	4	5	4	6		
DE475-102N21	2009	1000	24		155	5500	5	5	5	8		
ST												
SCT 30N120*	2016	1200	45		105	1700	19	28	45	20		
SCT20N120 K5*	2019	1200	20	0.19	45	650	10	17	27	16	y	
STW 6N120K3	2012	1200	6		39	1050	30	12	58	32		
STW 12N120K5	2015	1200	12	0.69	44	1370	23	11	29	18	y	
STL 57N65M5#	2015	650	22		96	4200	84	11	11	17		
STL 21N65M6#	2015	650	17		44	1960	37	10	12	24		
Infineon bought out IR	Bit slow											
Wolfspeed was Cree SiC												
C2M0080120D*	2015	1200	36		62	950	11	20	23	19	y	
C3M0350120D*	2020	1200	7	0.35	19	345	25	16	14	17	y	
ROhm												
2080KE*	2015	1200	40		106	2080	35	36	76	22		
2160KE*	2021	1200	22	0.15	62	1200	23	25	67	27	y	
On Semi bought out Fairchild												
FCPF 400N80Z	2015	800	14		43	1770	10	6.4	22.7	14		
FCB 290N80	2015	800	17		58	2410	22	14	61	2.6		
United SiC												
UJ3C120080K3S	2018	1200	33		51	1500	22	14	61	14		

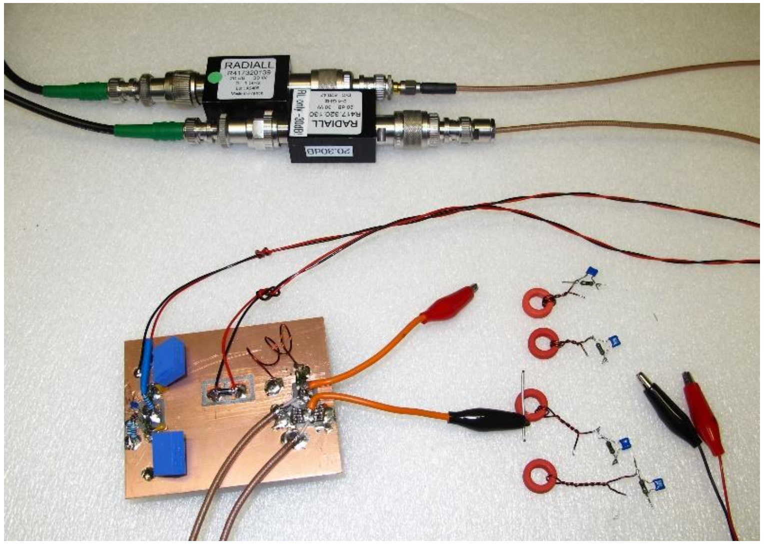
Table 1(a) FET types. Brown line is the original type.

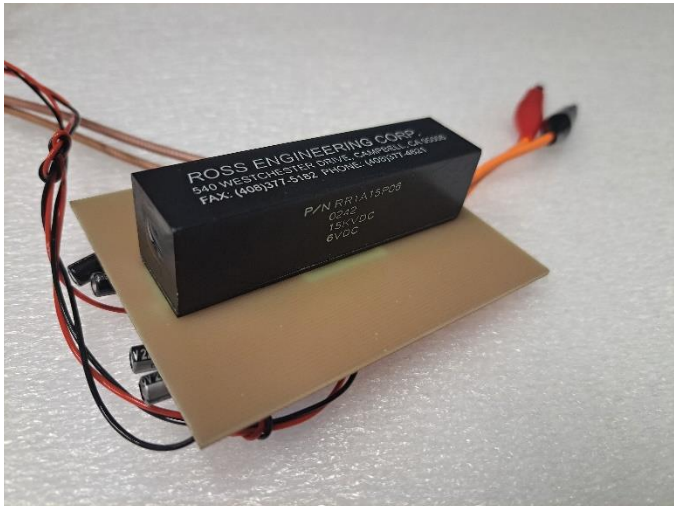
Pulse Measurement of Ring Cores for Gate Transformer - 1

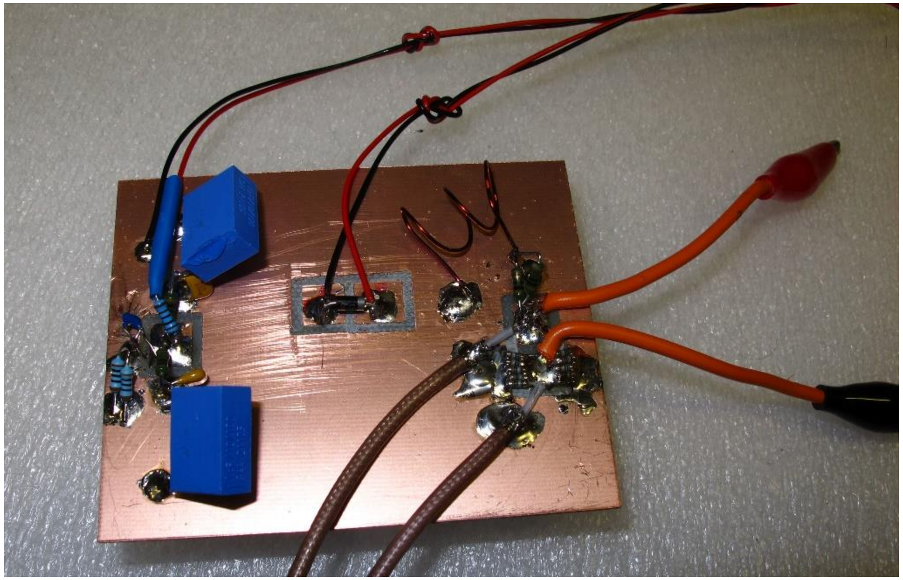


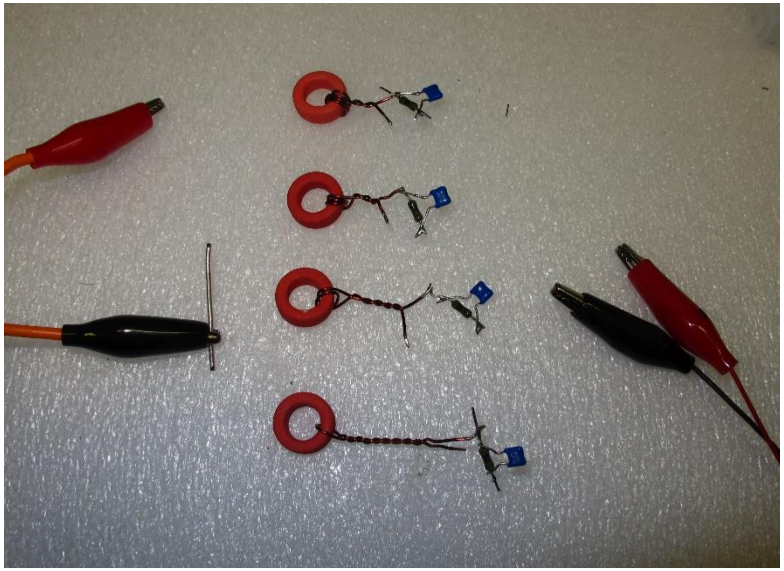


Pulse Measurement of Ring Cores for Gate Transformer - 2



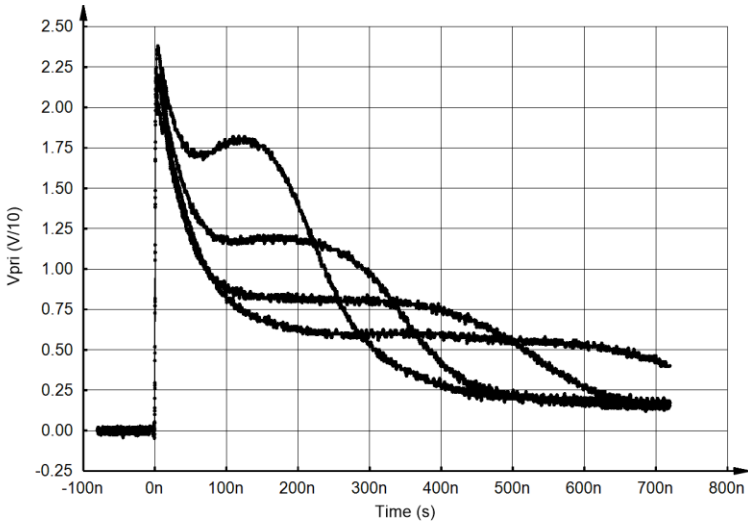


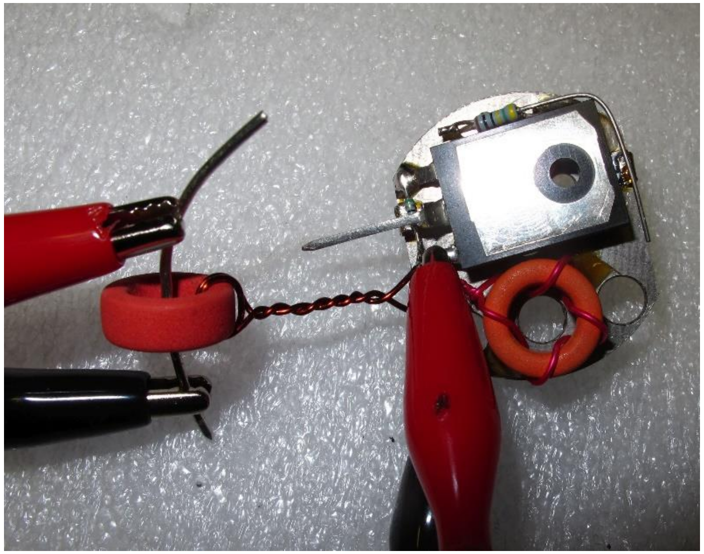


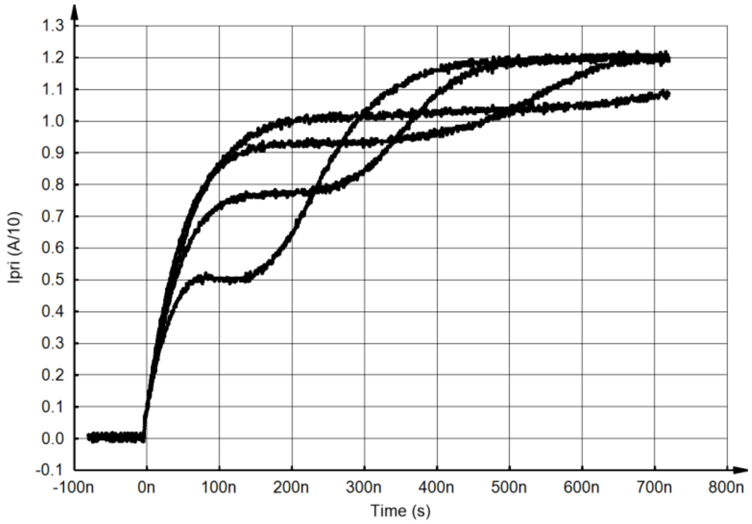


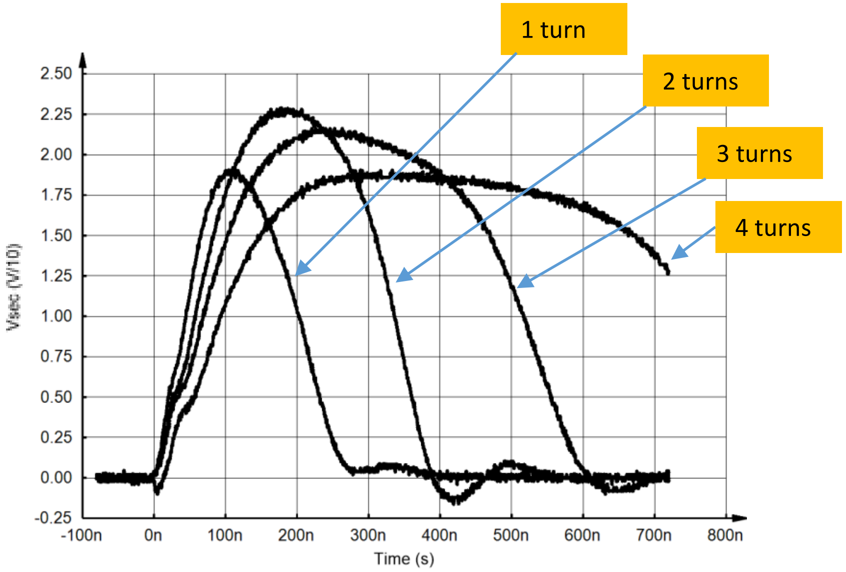
Pulse Measurement of Ring Cores for Gate Transformer - 3

1,2,3 and 4 Turns, with 14/9/4 MnZn,with R=10 and MOSFET (Vds=0) as load



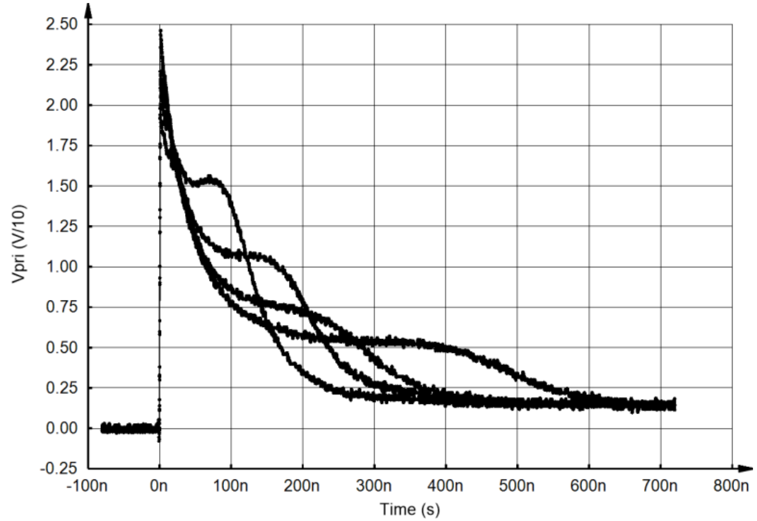


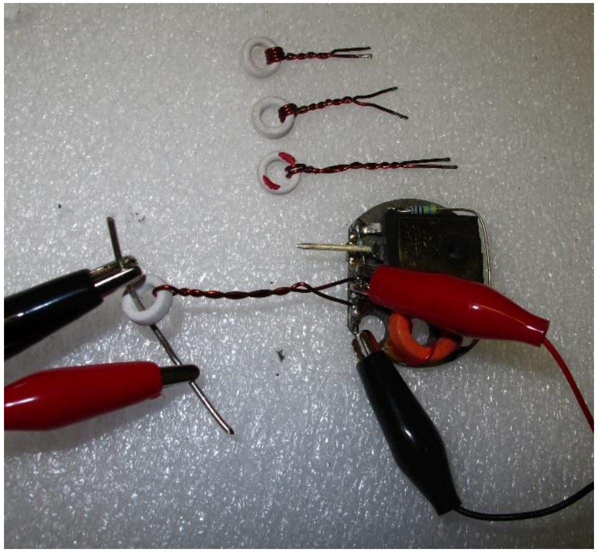


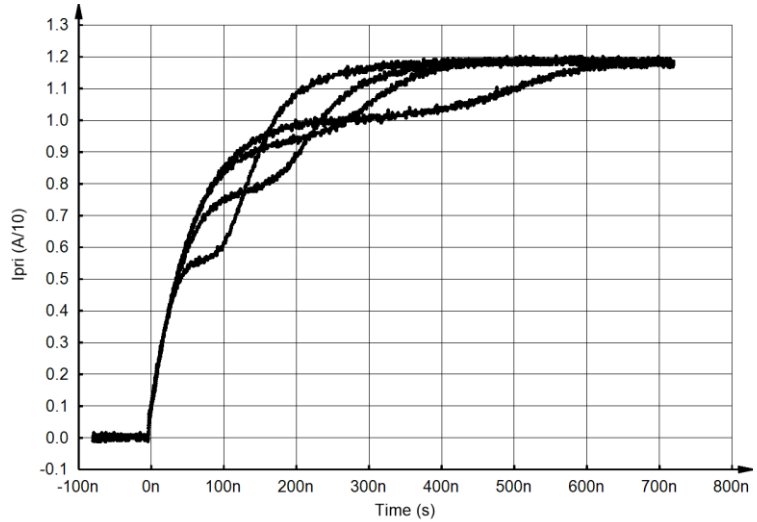


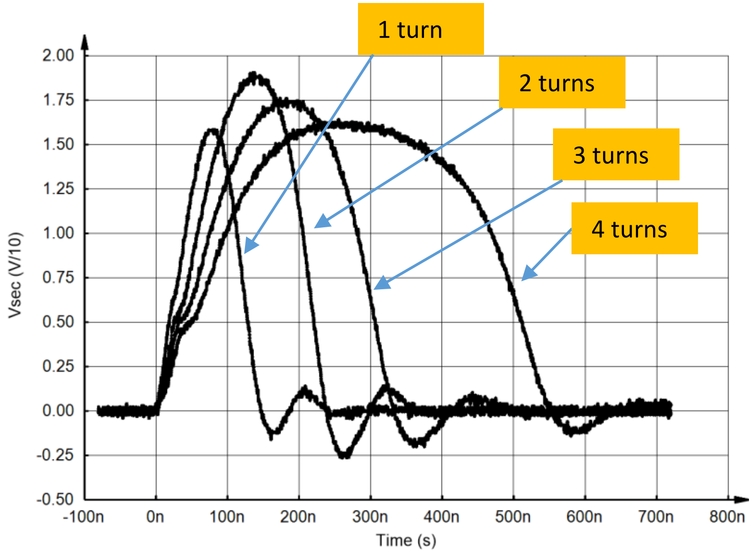
Pulse Measurement of Ring Cores for Gate Transformer - 4

1,2,3 and 4 Turns, with 9/6/3 MnZn,with R=10 and MOSFET (Vds=0) as load









Pulse Measurement of Ring Cores for Gate Transformer - 5

Basic circuit is transformer with primary and secondary resistance – the capacitance of the FET gate on the transformer secondary slows the rise time, predictably, but is not the main interest.

For this study, subjective choice to put 10 Ohm resistor on secondary, as low as possible to limit unwanted dV/dt turn-on of the FET via the Miller capacitance

With the condition that the secondary resistance is $<100\ \Omega$, the secondary voltage is largely independent of the core turns ratio !

Only two ring core materials easily available:

- MnNi
- low mu (typ.60) and Al (typ.70nH)
- MnZn
- very high mu (2000-10000) and Al (typ. 2.5uH)

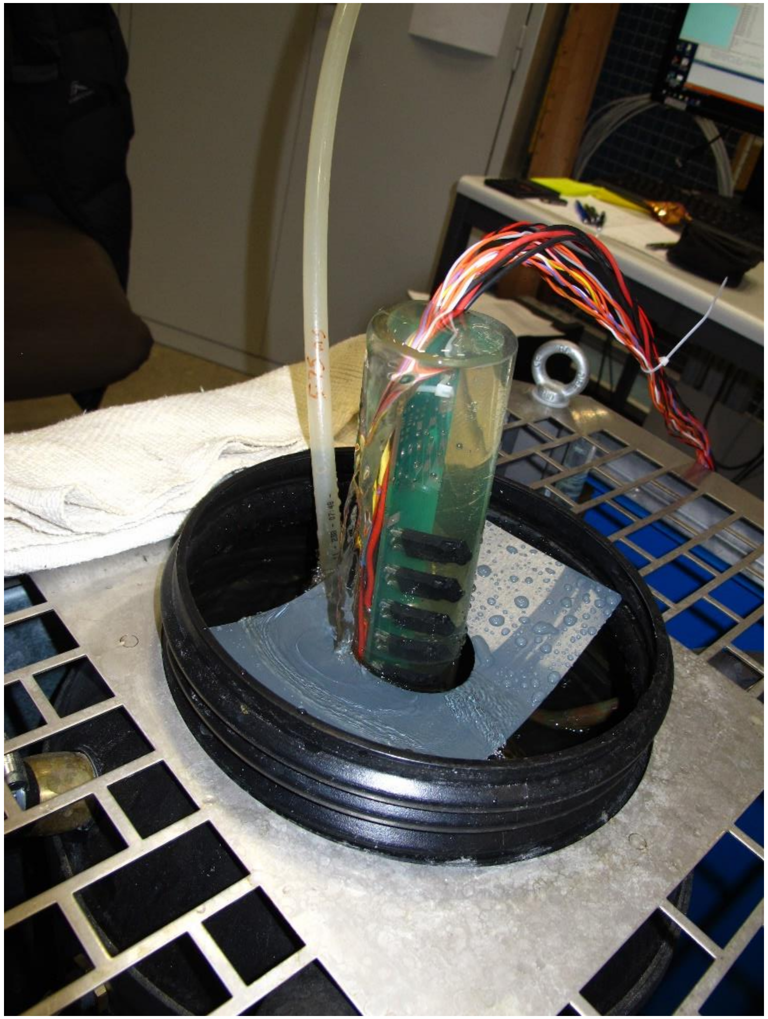
With 1:1 transformer, MnNi cores give typically 50% voltage loss, so unacceptably large leakage inductance

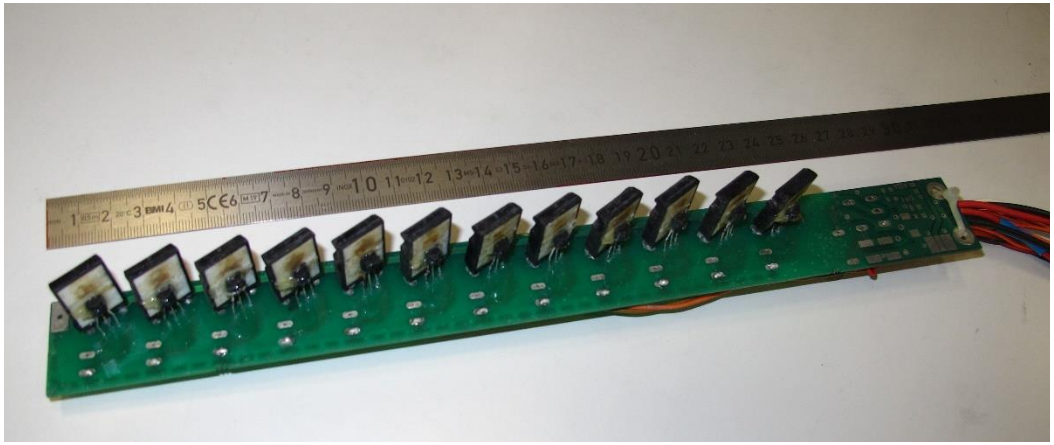
To conclude, use:

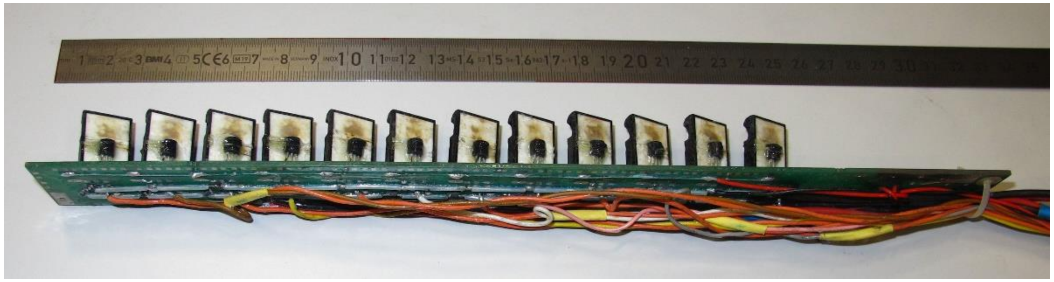
- MnZn material
- 14/9/6
- 1:1 turns ratio
- 20V / stage
- Minimise stray L for rise time
- Natural decay of gate voltage, no tight constraint on turn-off pulse

Heat removal from TO-247 transistors - 1

PCB fitted with 12 resistors in TO-247 packages
Temperature sensors epoxied onto resistors
Whole assembly sprayed with conformal coating
Demineralised water in a commercial chiller
After some hours all the metal surfaces were corroded, but not enough to invalidate measurements

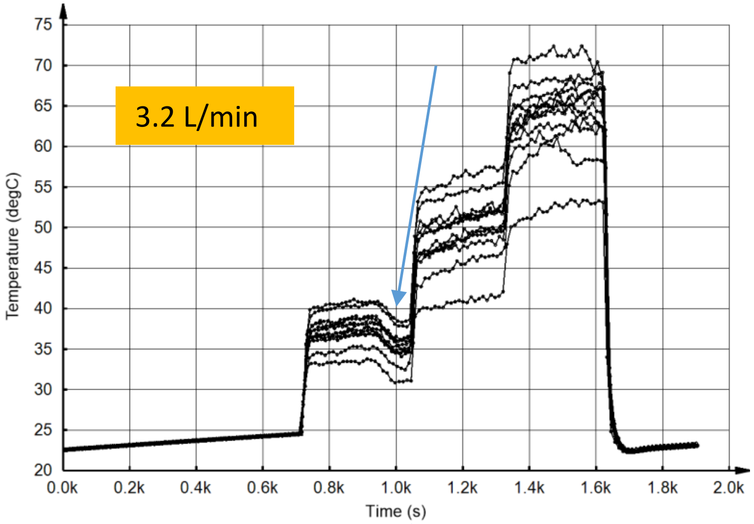




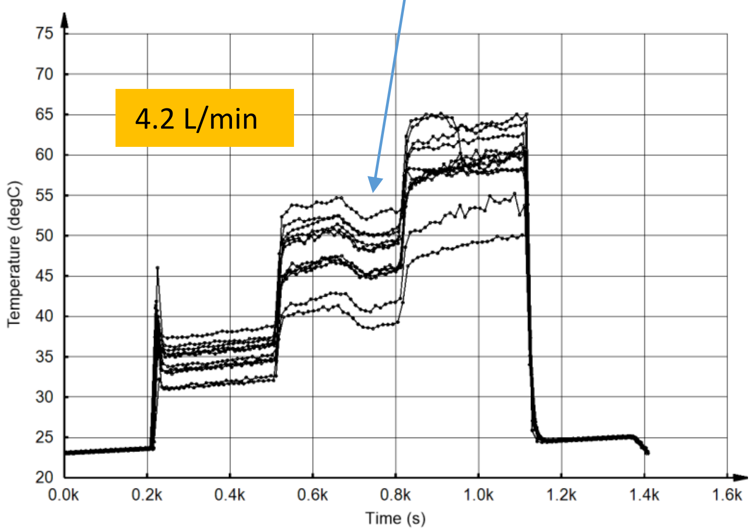


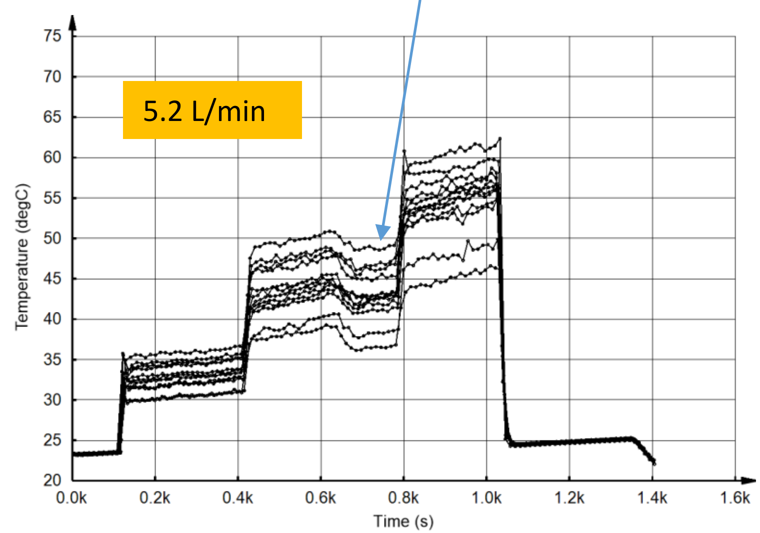
Heat removal from TO-247 transistors - 2

In ca. ten minute steps, the total power dissipated was increased 100W, 200W, 300W



Artifacts - dips in temperature due to normal hysteresis in chiller cooling cycle





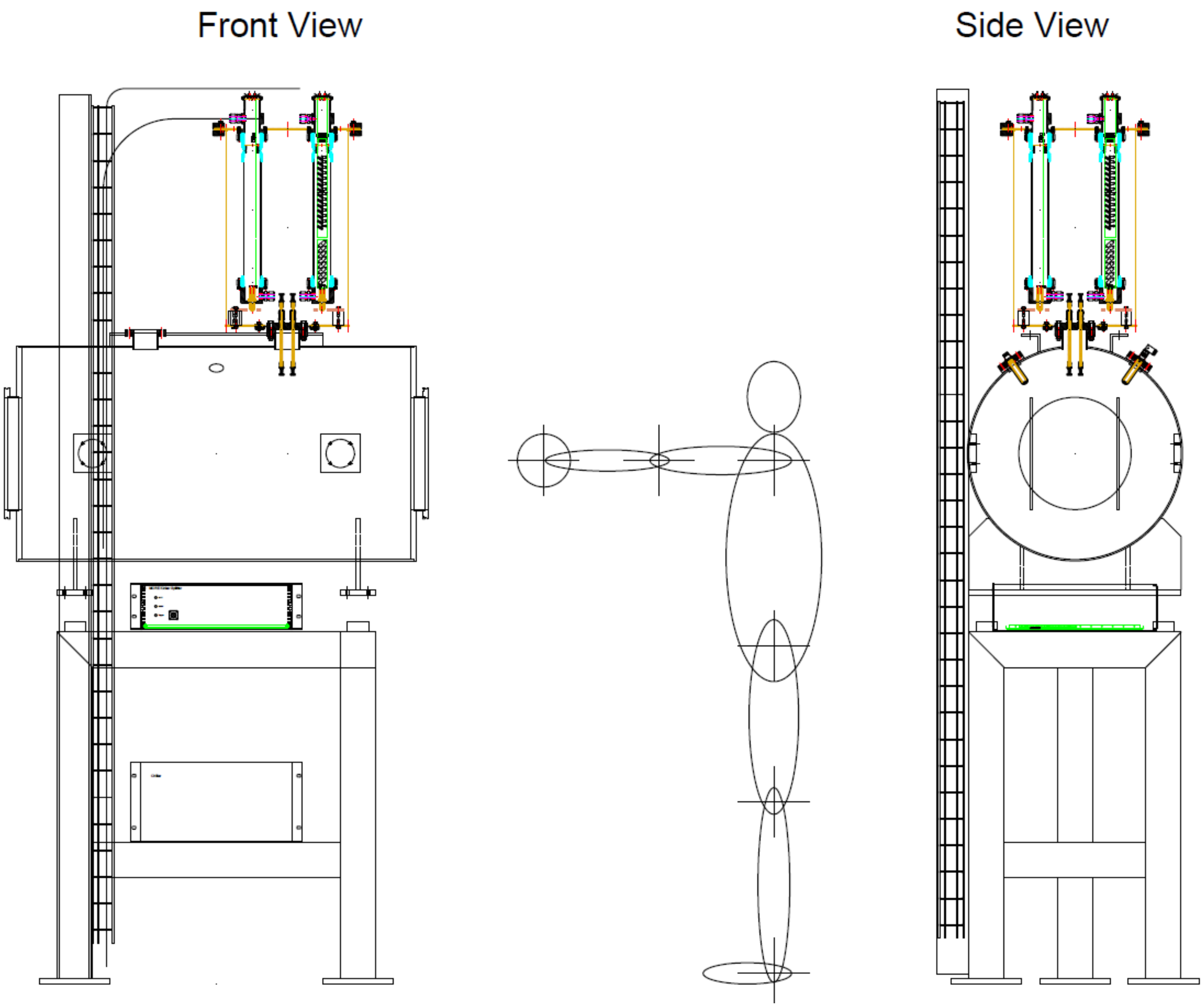
Heat removal from TO-247 transistors - 3

To conclude:

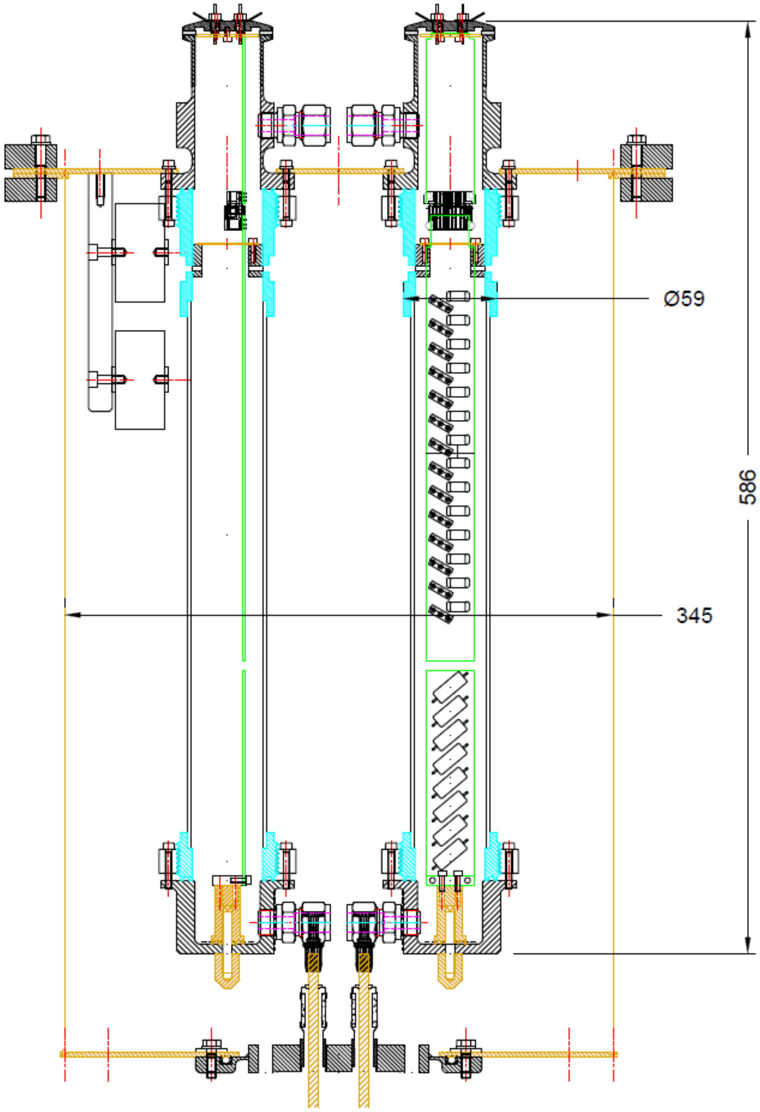
- modest “shadowing” of coolant flow may occur
(e.g. the first transistor may be cooled more than the rest)

- choose 4L/min to give ca. 60 deg.C transistor temperature

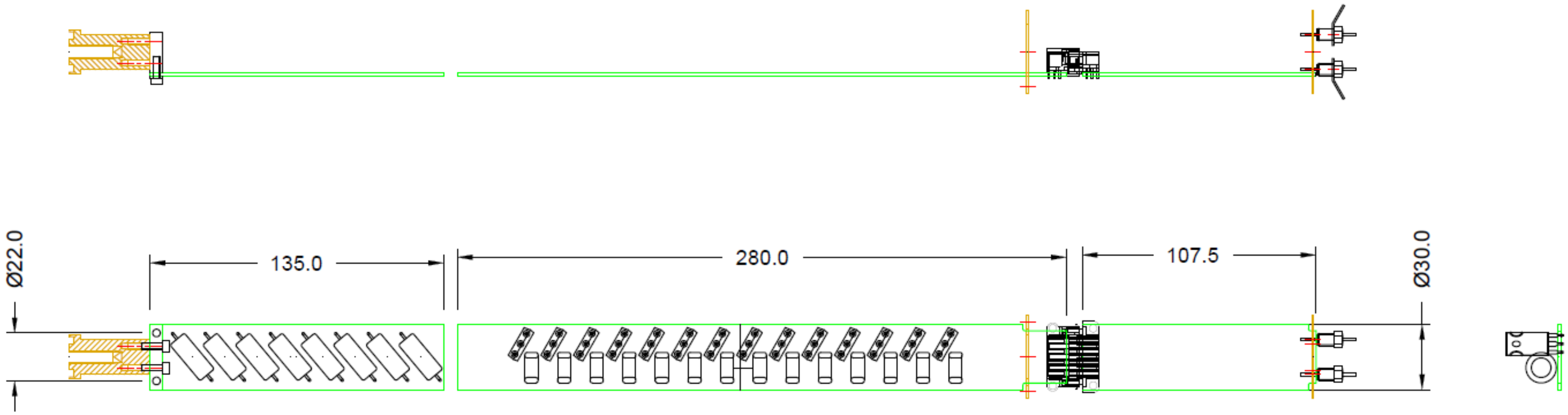
New mechanical design- 1



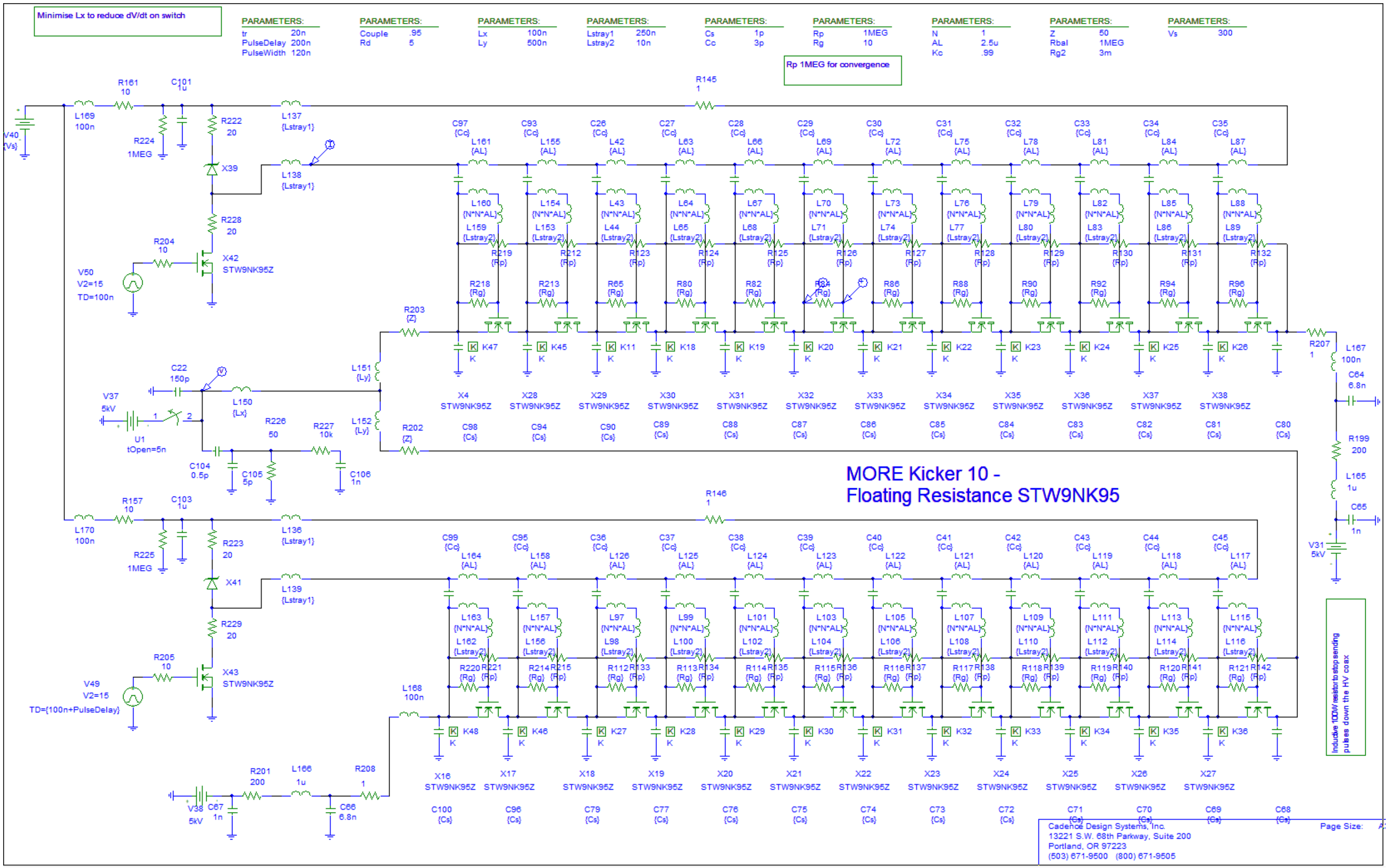
New mechanical design - 2



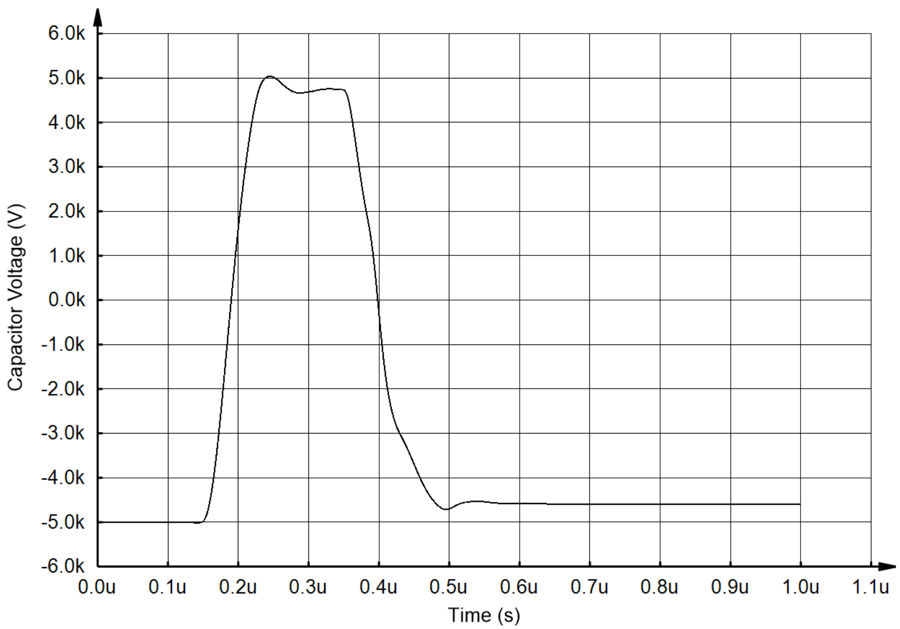
New mechanical design - 3

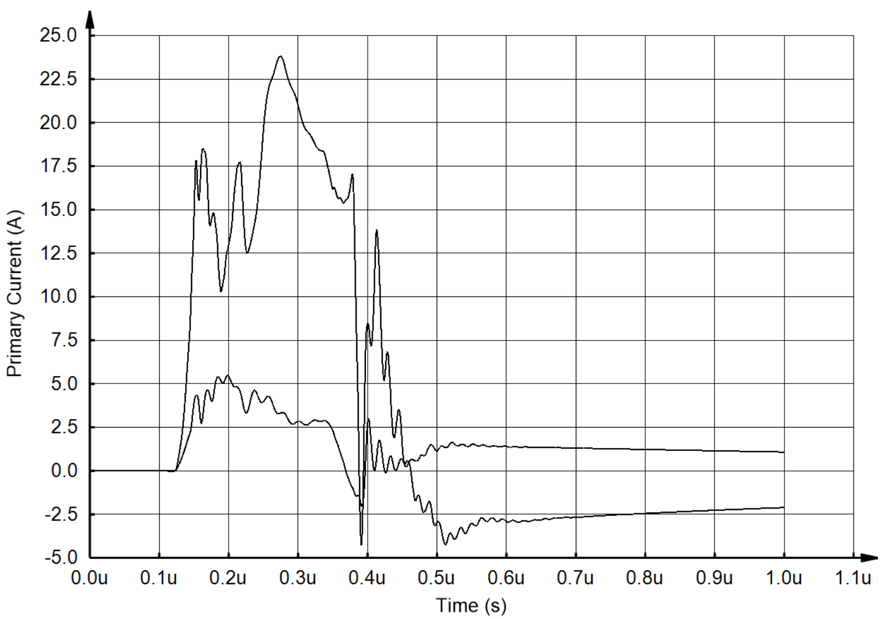


Pspice circuit simulation - 1



Pspice circuit simulation - 2





As demonstration - shortest possible pulse

Simulation of primary current and secondary voltage has unrealistic oscillations

Summary

Original switch design from 1995 was inspired ! Too bad it was destroyed by cooling water leaking into the FC-77 Fluorinert.

The requirement for <50ns latency is a problem with simple transformer-coupled switch. But given the long trigger cables to this kicker, the “50ns” requirement is a bit arbitrary.

The main technical difficulty is the cooling. Measurements with a dummy PCB indicate that the system is sufficient.
After extensive efforts to find alternatives, cooling by forced convection of FC-77 Fluorinert was the only choice.
It is:

- non flammable
- non hygroscopic
- has environmental concern as a very volatile greenhouse gas, but large quantities remain in use for the PSI HIPA under strict control – the present kickers would use only about 4 Liters.
- complete immersion guarantees there is no HV breakdown between closely spaced PCB components, even over decades of use
- has low viscosity and forced flow guarantees cooling

Present upgrade can not “improve” much, Small changes are:

- Gate transformer with 1 turn secondary
- Flat PCB
- Mechanical design with O-ring sealing for the FC77 coolant
- Commercial self-contained solid state chiller (22kEur) to avoid expensive effort from in-house cooling group.

Reserve Material

Alternative Hardware - 2

1932 IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 32, NO. 5, OCTOBER 2004

A 25-kV 75-kHz Kicker for Measurement of Muon Lifetime

Michael J. Barnes, *Member, IEEE*, and Gary D. Wait

***Abstract*—An international collaboration plans to measure the lifetime of the muon to a precision of 1 part per million [1]. The "MuLan" experiment will take place at the Paul Scherrer Institut (PSI) in Northern Switzerland. The MuLan experiment requires a fast beam line kicker, which can turn the beam on and off, to invoke an artificial time structure on the continuous beam which has a 50.6-MHz time microstructure. The kicker needs to run with a standard "on-off time cycle" or in a "Muon on Request" mode. The MuLan kicker consists of two pairs of deflector plates mechanically in series, driven by four modulators. Each modulator consists of two stacks of MOSFETs operating in push-pull mode. The specifications for the kicker demand that the rise and fall times of the deflector plate voltage do not exceed 45 ns. There is a requirement for an adjustable output voltage from 0 V to ±12.5 kV per deflector plate, a minimum pulse duration of 200 ns, and adjustable repetition rate up to a maximum of 50 kHz, continuous. Short turn-on and turn-off delays are required for the "Muon on Request" mode; the measured propagation delay is 200 ns. The specifications also require that the polarity of the pulses on the plates be selectable, although not on a pulse-by-pulse basis. This paper describes the novel design of the kicker and presents both predictions and measurements.**

***Index Terms*—Circuit simulation, electric fields, electrostatic devices, kicker, mesons, MOSFET power amplifiers, particle beam choppers, particle beam steering, power FET amplifiers, power FET switches, power FETs, power MOSFET switches, power MOSFETs, pulse generation.**

of +12.5 kV and the other plate of each pair is driven to a maximum of −12.5 kV. Therefore, the potential difference between a pair of deflector plates is variable up to 25 kV. Each pair of plates is 0.75 m long, 200 mm wide, and 5 mm thick, with a 2-mm radius on the edges, separated by 150 mm and housed in a beam pipe with an inside diameter of 600 mm. There is a virtual ground halfway between each pair of plates, which is a consequence of these plates being at equal voltage but opposite polarity. The two pairs of plates are separated longitudinally by 50 mm between the end of one pair and the start of the second pair.

The angle of deflection (θ_e), in radians, due to an electric field between the deflector plates, is given by

$$\theta_e = \arctan\left(\frac{V * \ell * c}{d * p * \beta * c}\right)\left[\frac{\mathrm{V}}{\mathrm{eV/c}}\right] \quad (1)$$

where V is the potential difference between the deflector plates (adjustable up to 25 kV), l is the overall length of the deflector plates (1.5 m), d is the plate separation (0.15 m), $\beta * c$ is particle velocity, c is the velocity of light in free space (3×10^8 m/s), and p is the beam momentum. From (1), a 30-MeV/c ($\beta = 0.28$) muon beam is deflected by 29 mrads, by a potential difference of 25 kV.

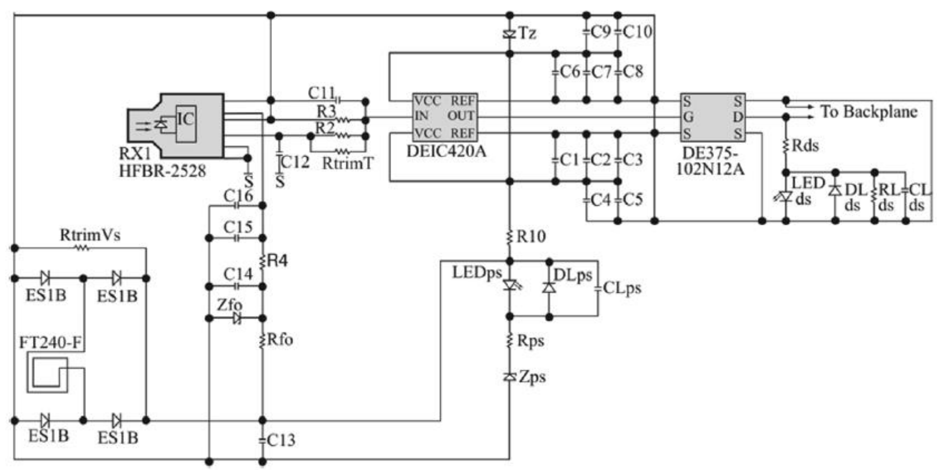
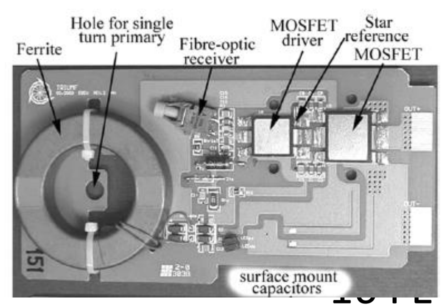
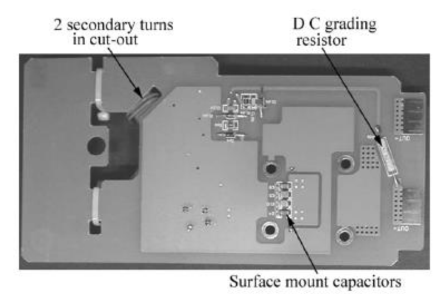
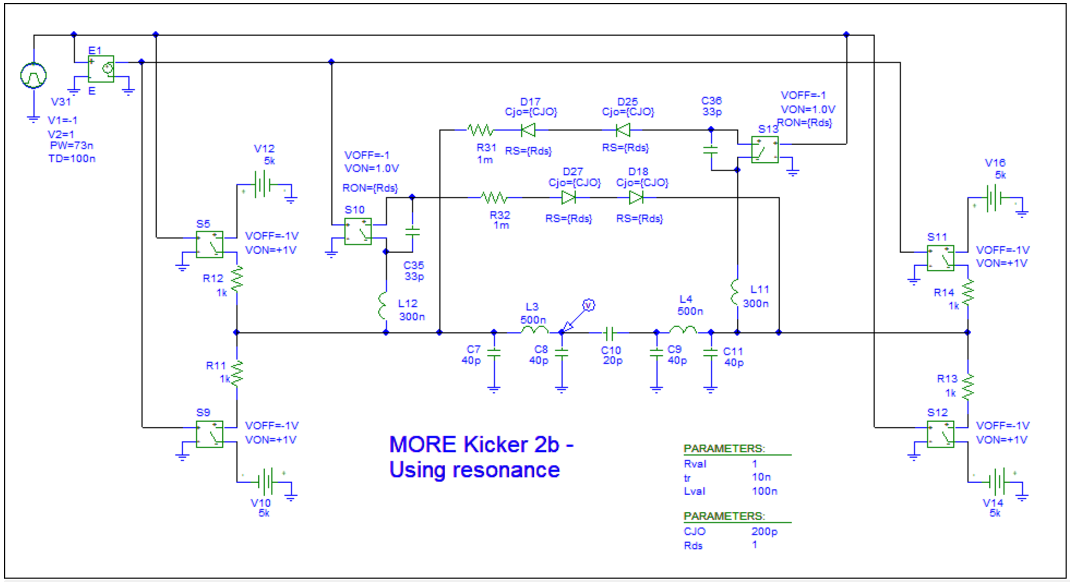


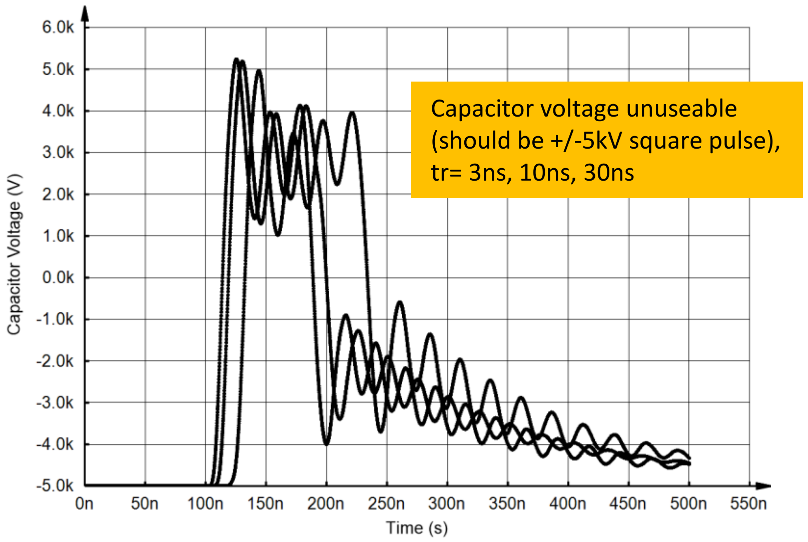
Fig. 2. Electrical schematic of a 1-kV module.

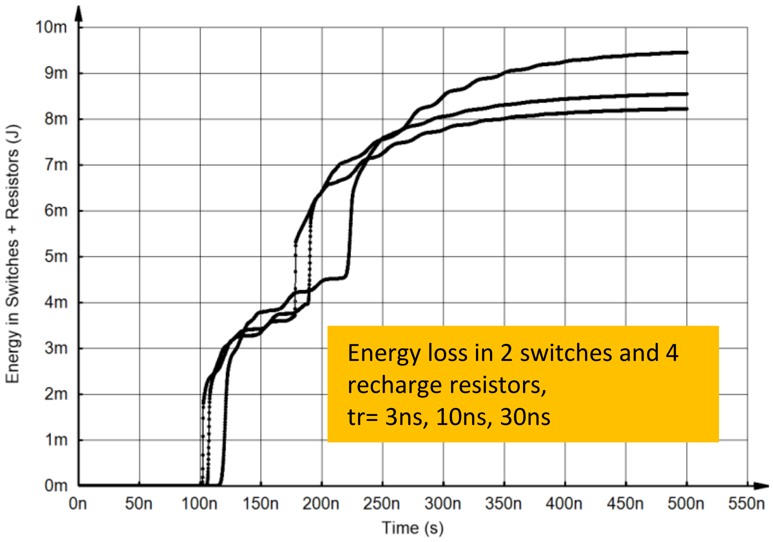




Attempt to use resonance impractical





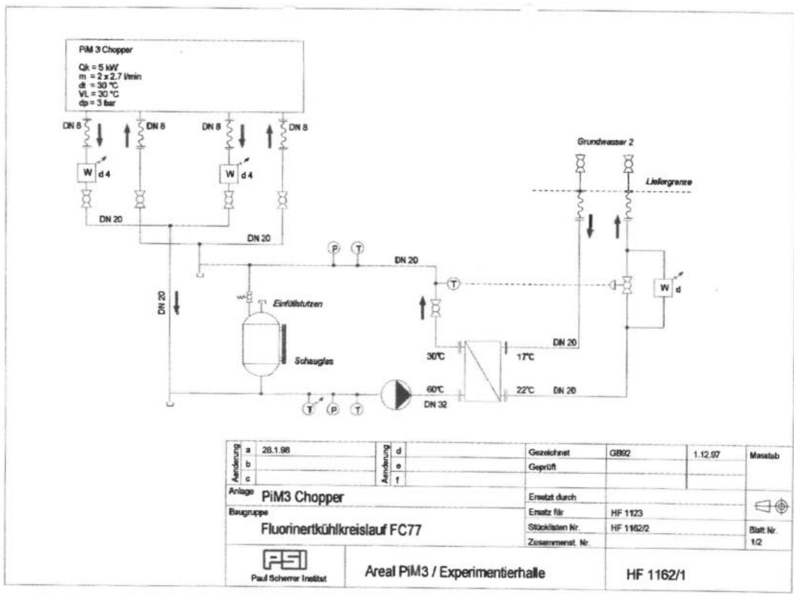


History

1. Introduction

The present situation was described in [1]. Project folders [2] contain all technical details photos etc from the development. The circuits from Goepf Irminger were dated 1994, and the pulser test (with a fan cooled system) by Roland Erne was dated 1995. In 1998 there was an order for a 310CHF soldered heat exchanger and a revised cooling system drawing. There was work to fix the FuG HCN1400-6500 supplies for in-rush current failures in 2002-2003. In 2013, the coax feedthrough cable failed and this was replaced with an "connector free" system. In 2013, the heat exchanger leaked water into the FC77 cooling fluid, which caused switch failure.

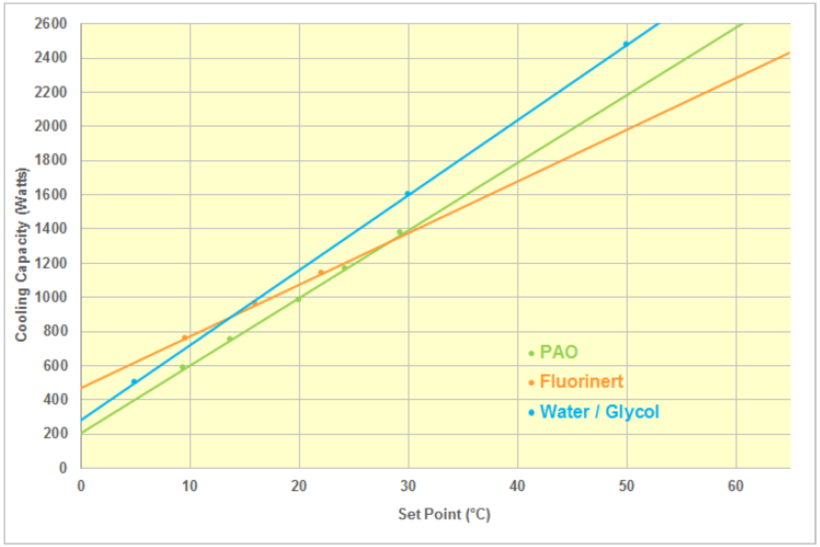
Cooling System



Cooling System

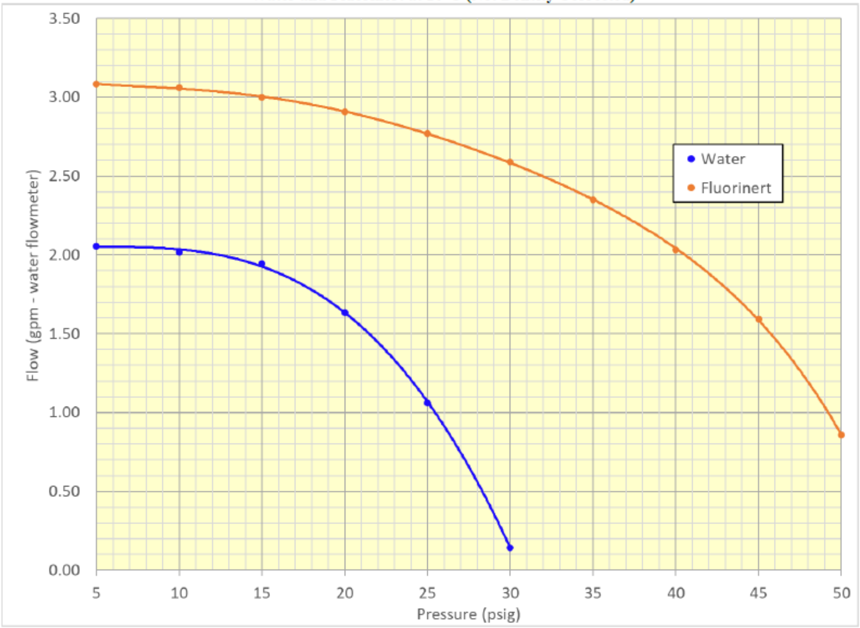
THERMORACK 1000 CHILLER PART # 52-12754-X

Figure 1: ThermoRack 1000 Cooling Curves at 20°C Ambient

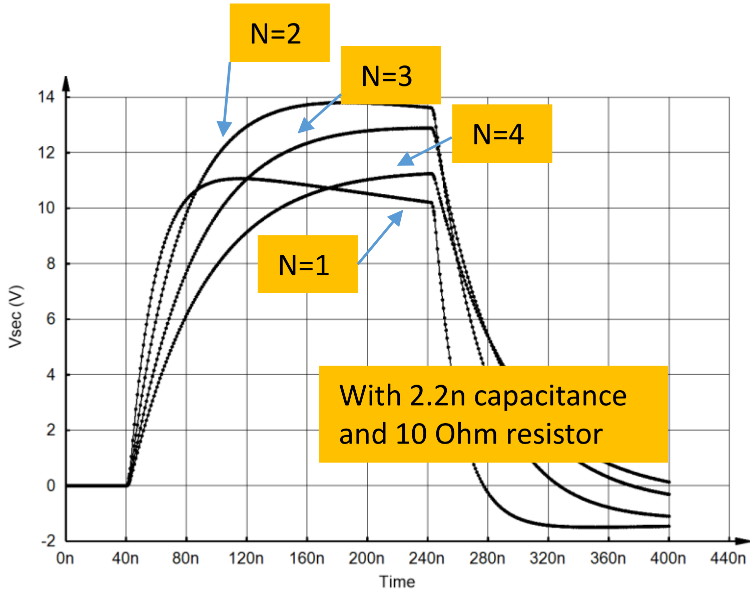


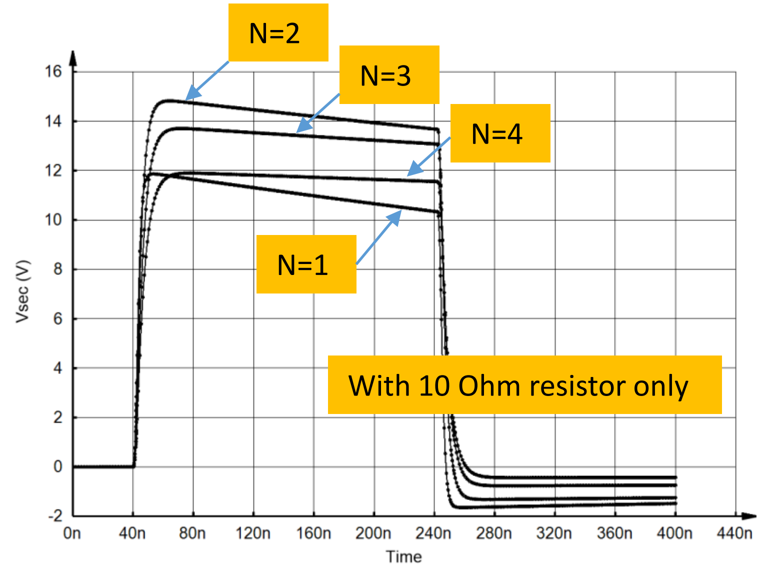
THERMORACK 1000 CHILLER PART # 52-12754-X

Figure 2C **Standard ThermoRack 1000 Centrifugal Pump Curves**
Water and Fluorinert at 20°C (Not Density Corrected)



SPICE simulation with Turns Ratio 1:1 to 1:4



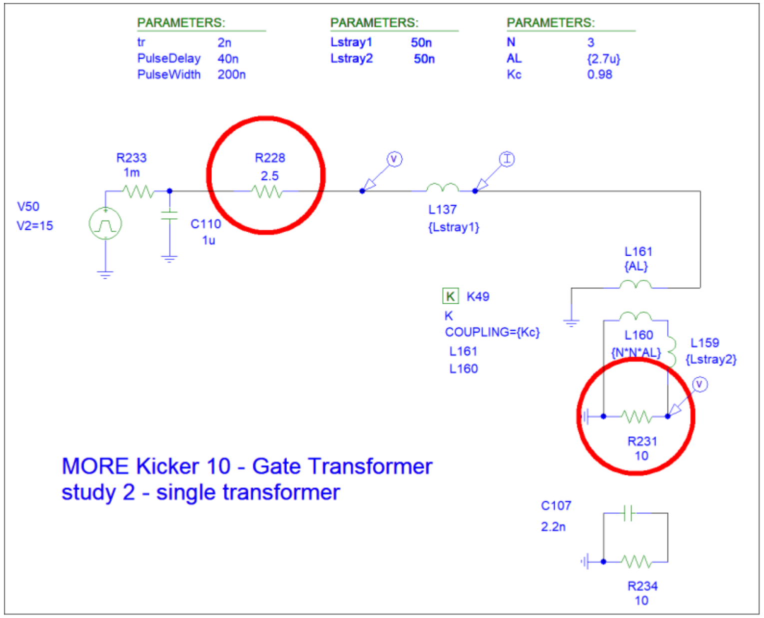


Secondary resistance subjective, fixed to 10 Ohms to give "reasonable" dV/dt immunity on FET

Primary resistance gives a limit to the primary current (in any case, MnZn core is completely saturated >5A)

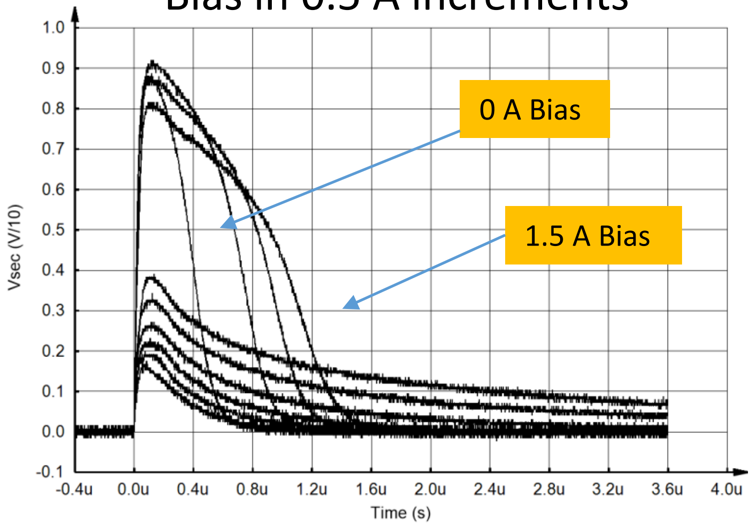
Rise time is minimized by minimising stray inductance in transformer, primary and secondary.

With this condition of low secondary resistance (<<100 Ohms), the secondary voltage is almost independent of turns ratio !

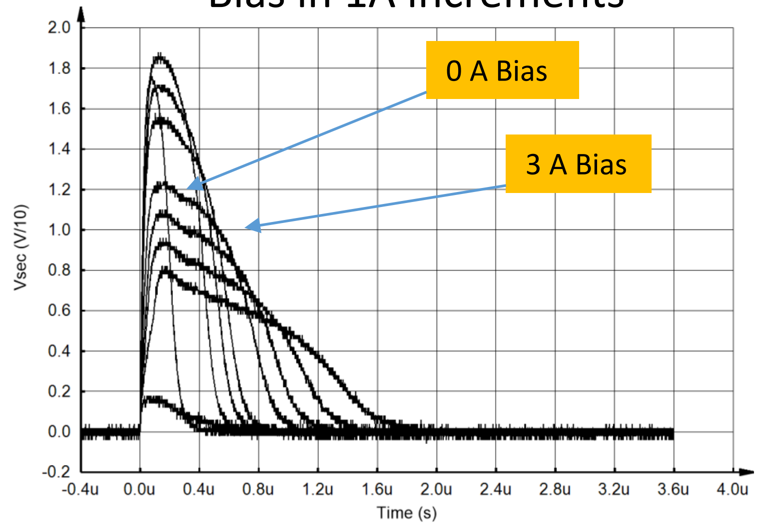


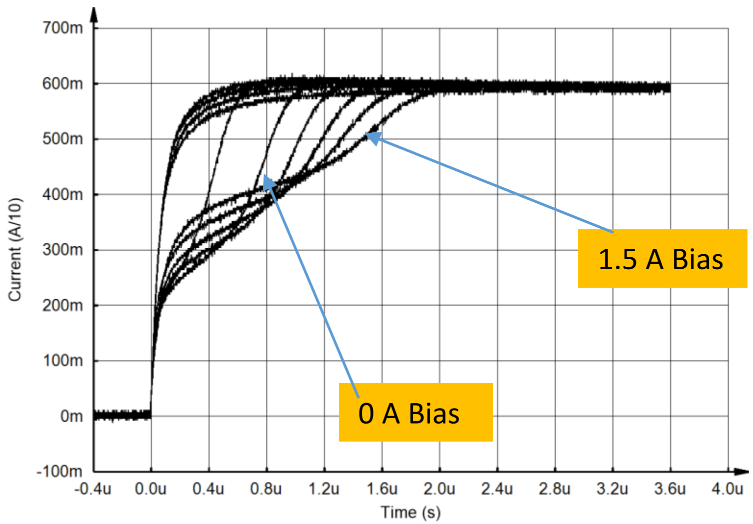
Effect of Core Bias, 1 Turn secondary

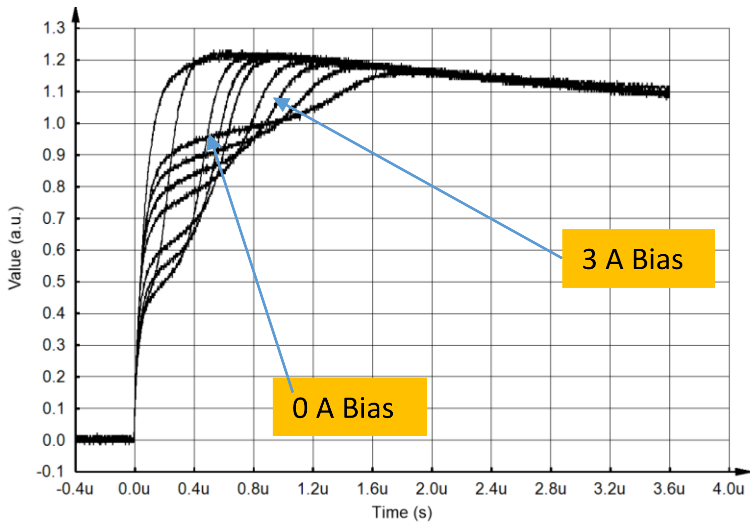
~11V / 6A limit on primary,
Bias in 0.5 A increments



~24V / 12A limit on primary,
Bias in 1A increments





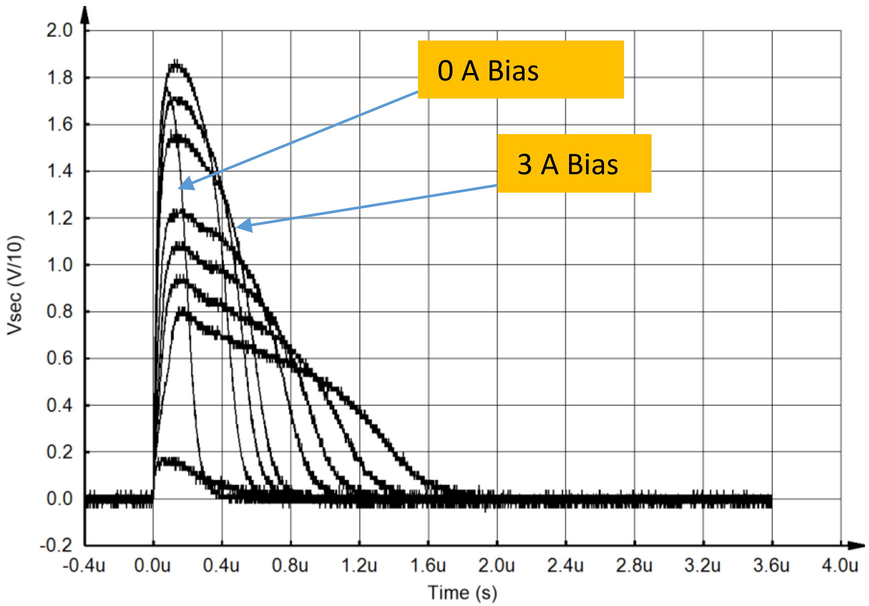


Conclude
No bias gives ca. 200ns pulse, small bias extends this to ca.400ns

1 Turn and 2 Turn Secondary, Effect of Core Bias

~24V / 12A limit on primary,
Bias in 1A increments

1 turn secondary



2 turn secondary